

Unlocking the Mystery of Columbia's Tragic Accident Through Materials Characterization

Presented to
Mississippi State University Materials Working Group
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Gregory Jerman
James Coston

October 15th, 2003

Acknowledgement: This work is a result of a team effort involving KSC, JSC, MSFC, LaRC, GRC, Boeing, USA and Columbia Accident Investigation Board personnel. ₁



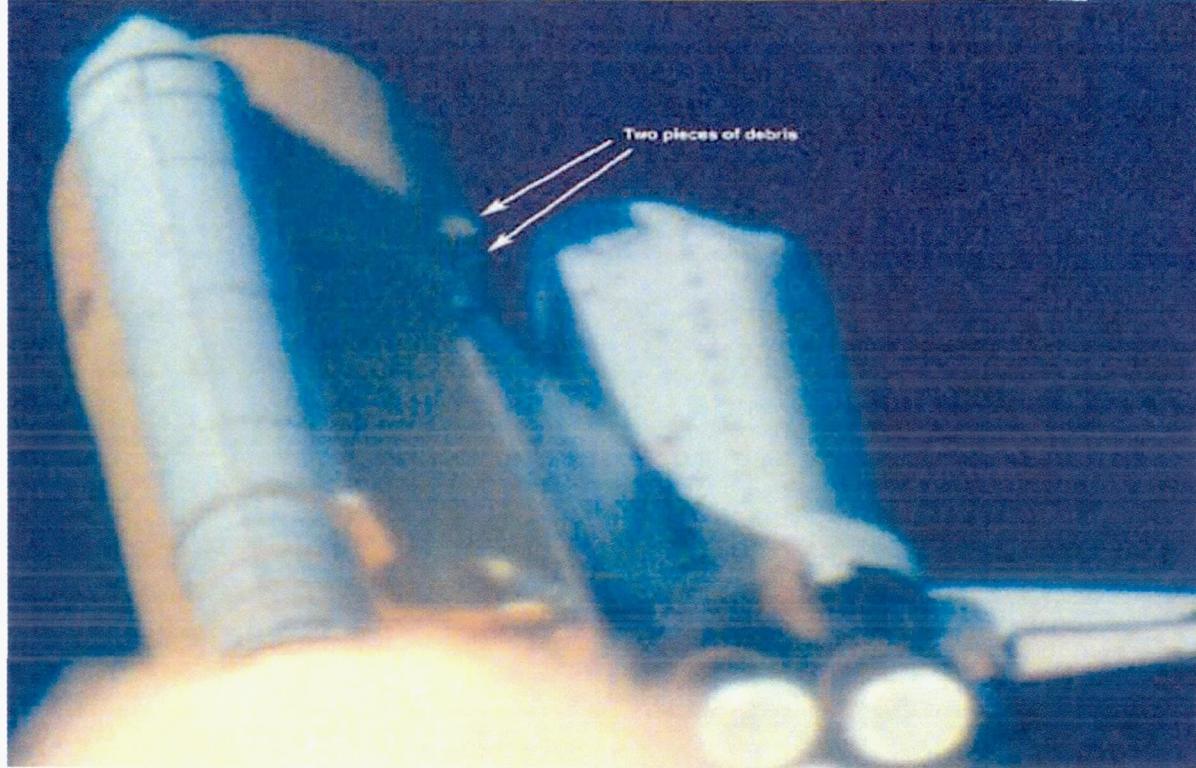
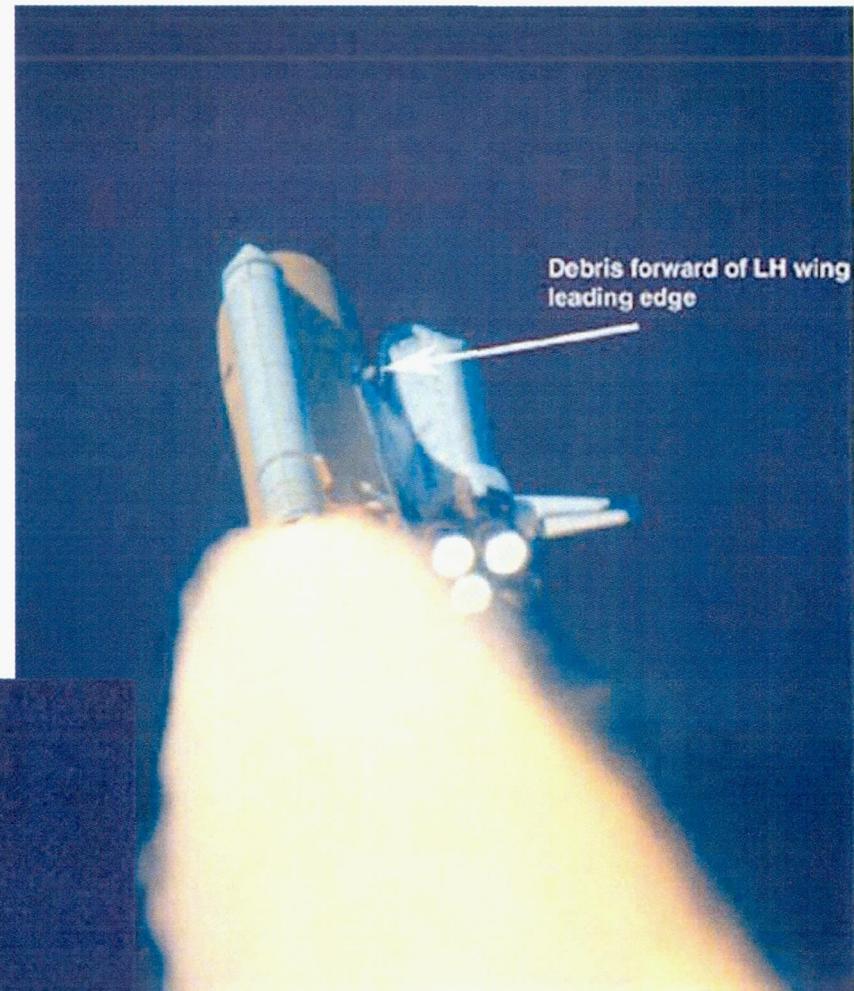
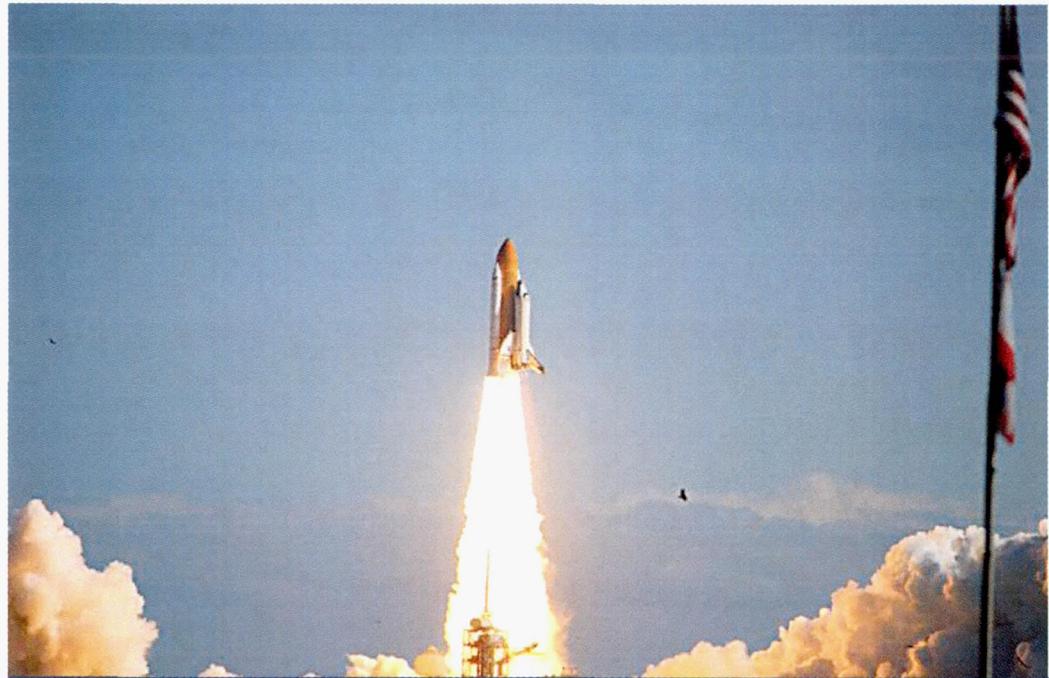
IN MEMORY
OF STS-107
ASTRONAUTS



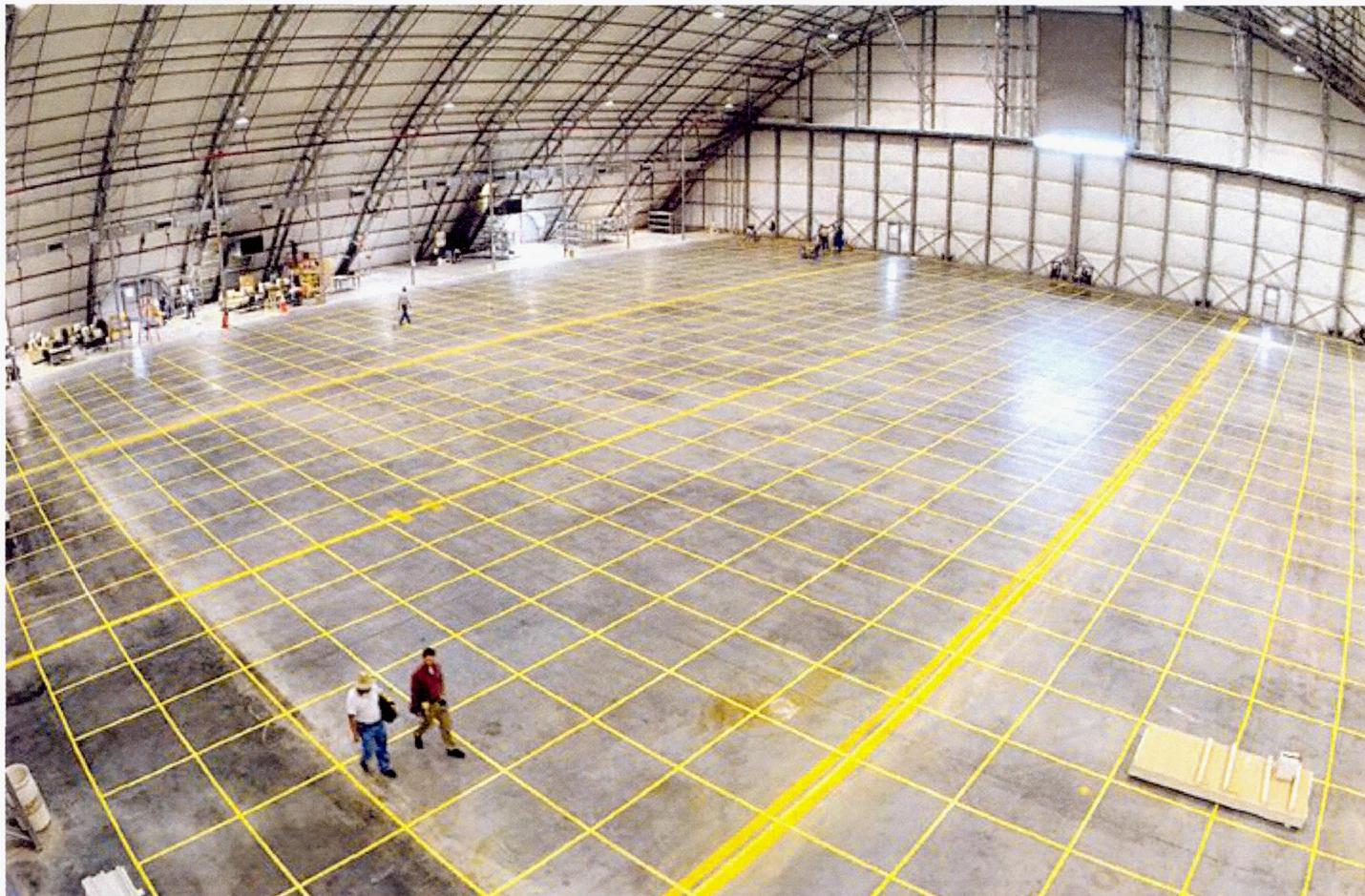
Space Shuttle Columbia In Orbiter Processing Facility (OPF) and Rollout to Vehicle Assembly Building (VAB).



STS 107 Rollout and on Launch Pad



STS107 Launch



Shuttle Landing Facility Hangar Prior to Debris Recovery



STS107 Reconstruction - Wing and Underbelly Surfaces Only



Right Wing

Aft

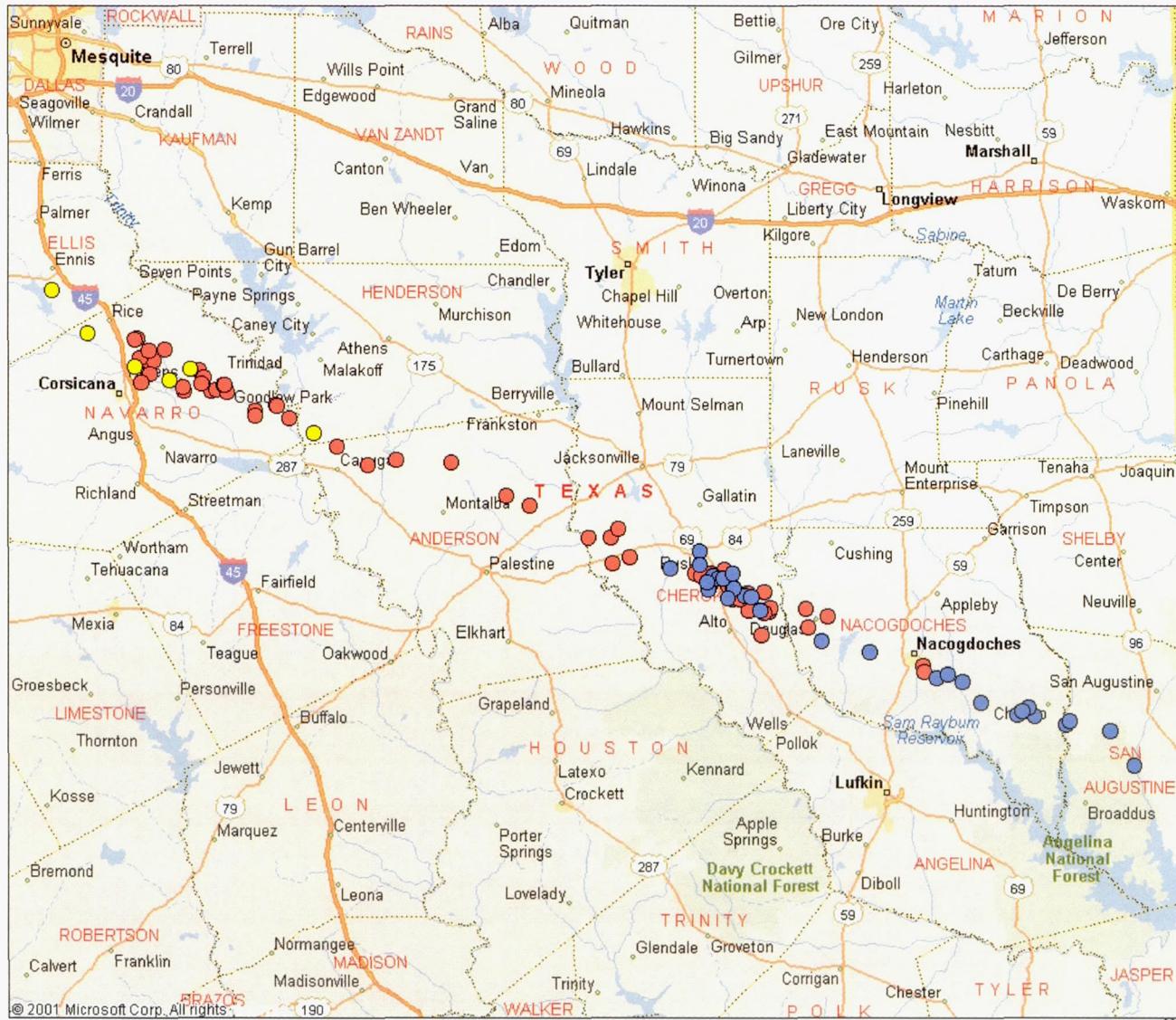
Forward

Location of each part found tracked on map - Trend emerges.

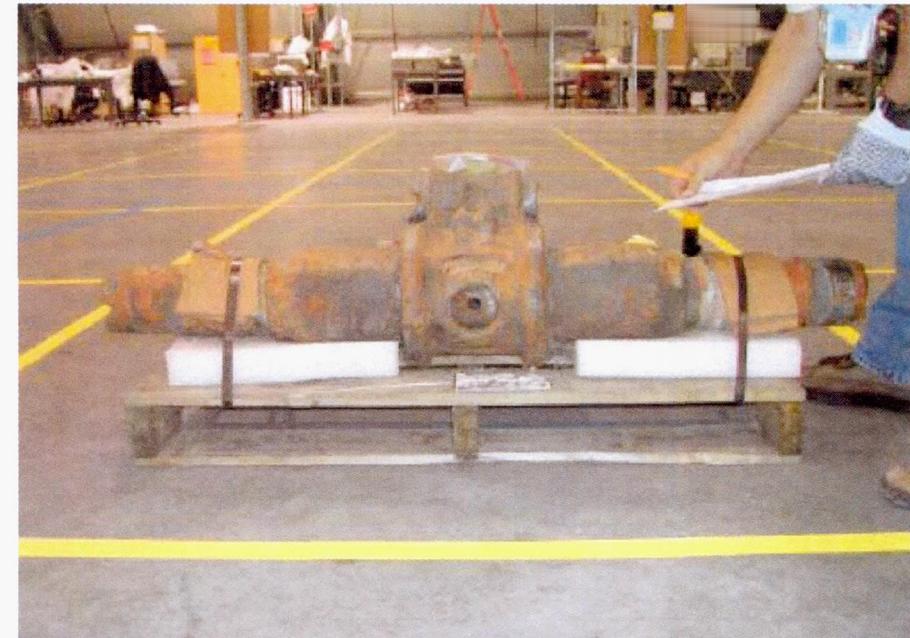
● Left Wing
RCC

● Left Wing
Eroded RCC

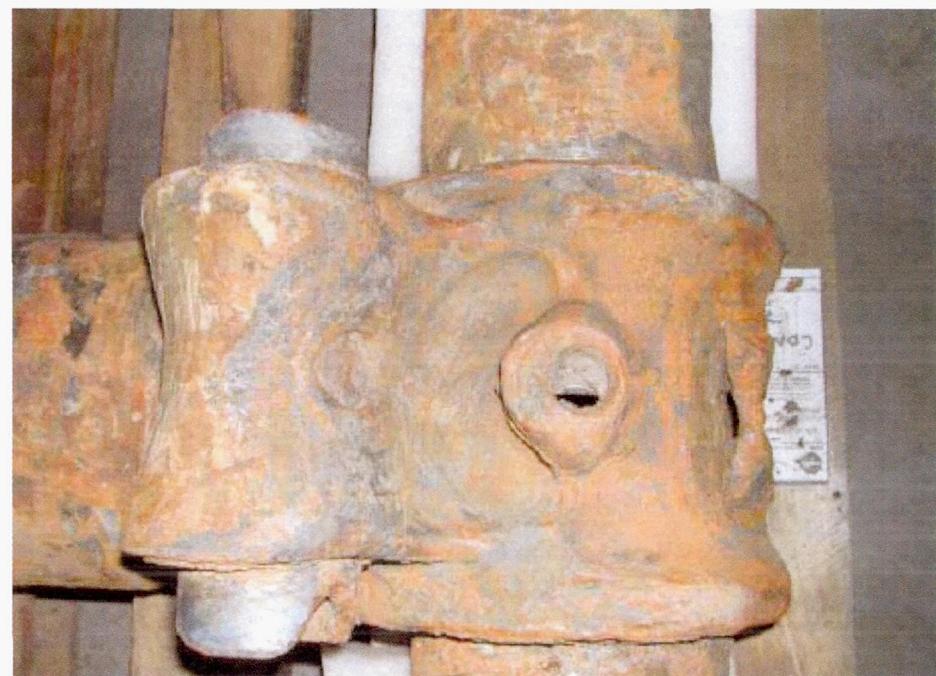
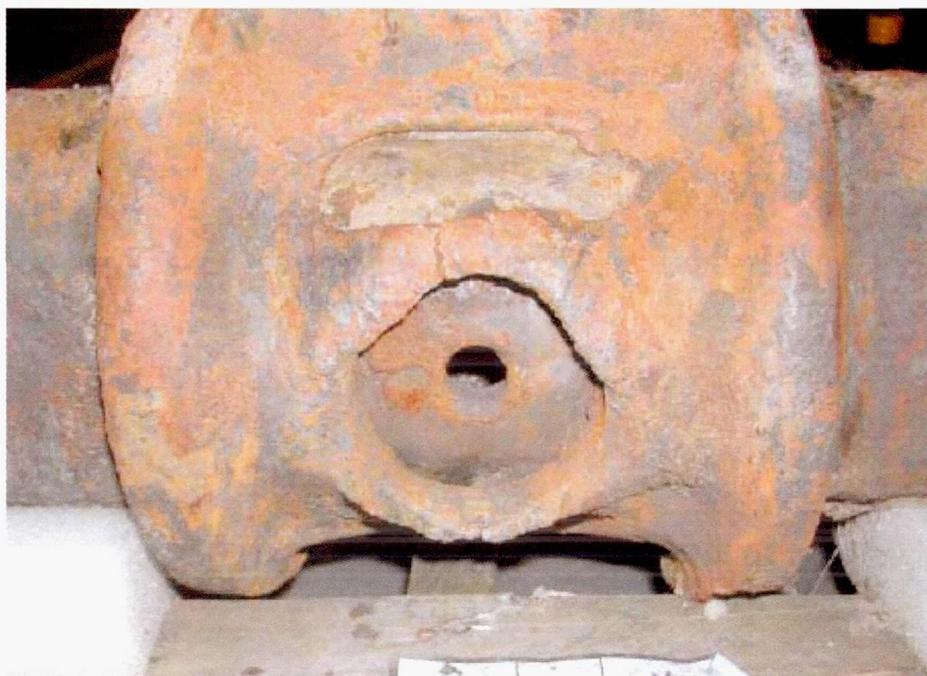
● Right Wing
RCC





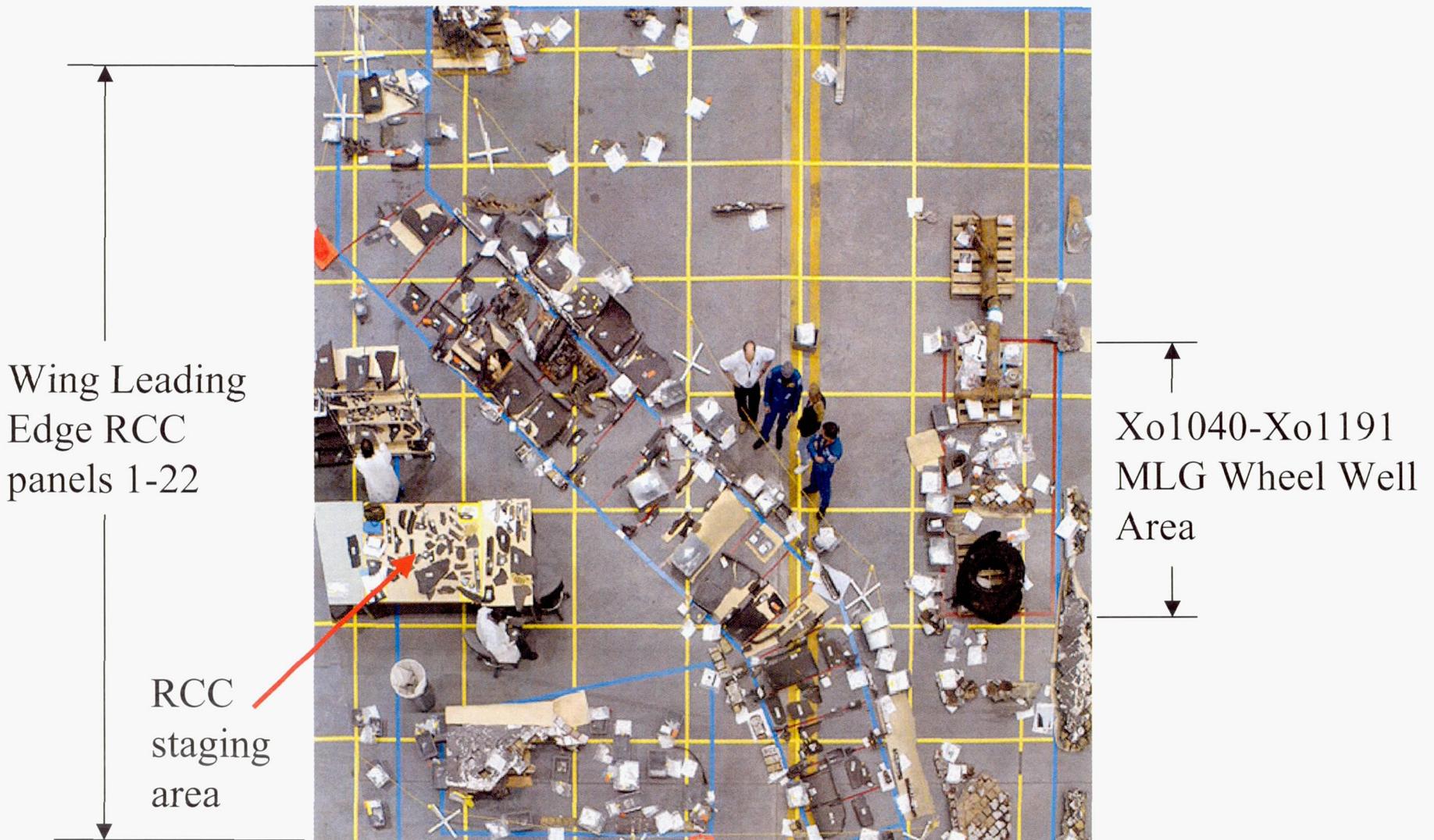


Believed to be Left Wing Main Landing Gear Assembly

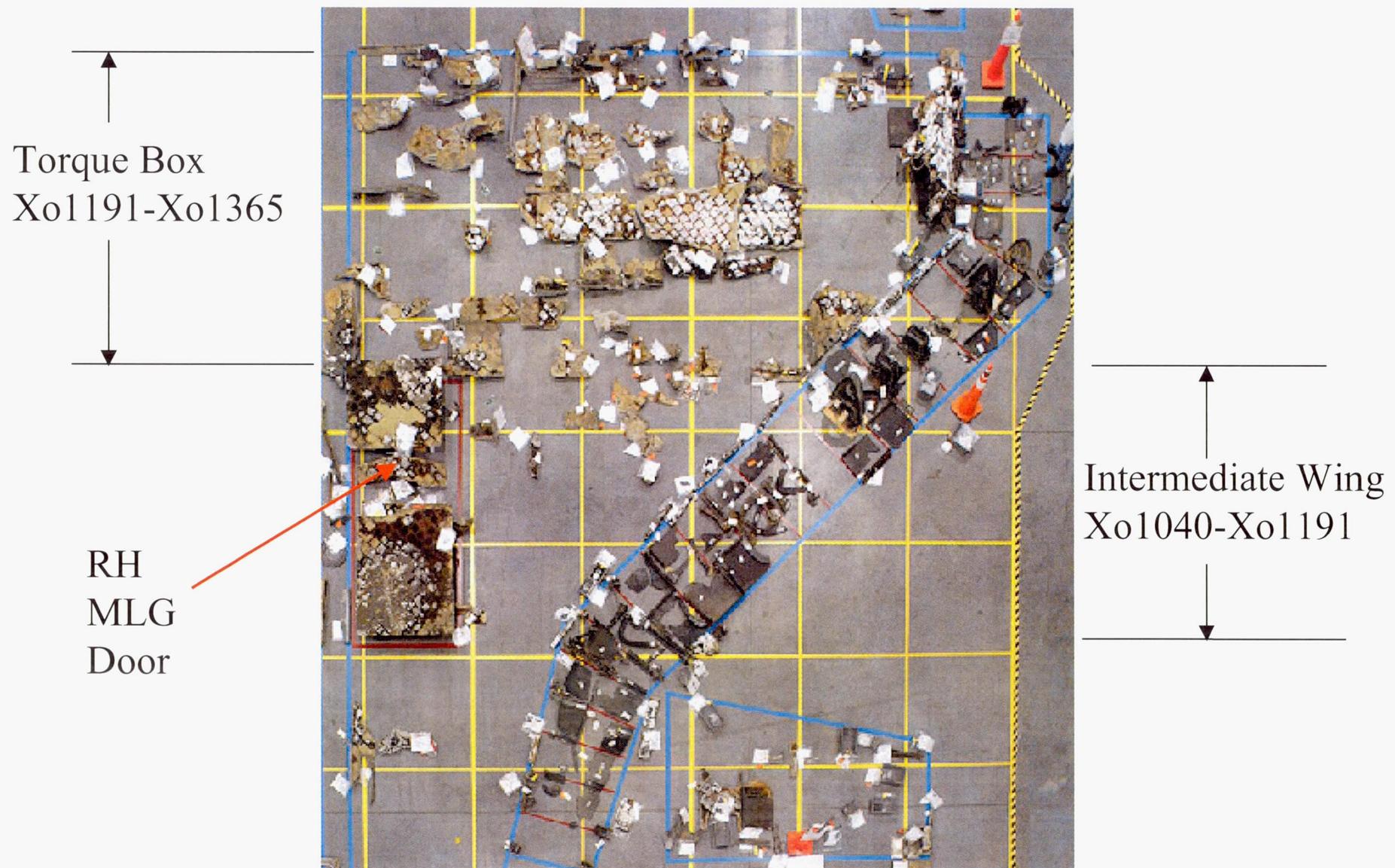




Part Adjacent to Left Main Landing Gear Door

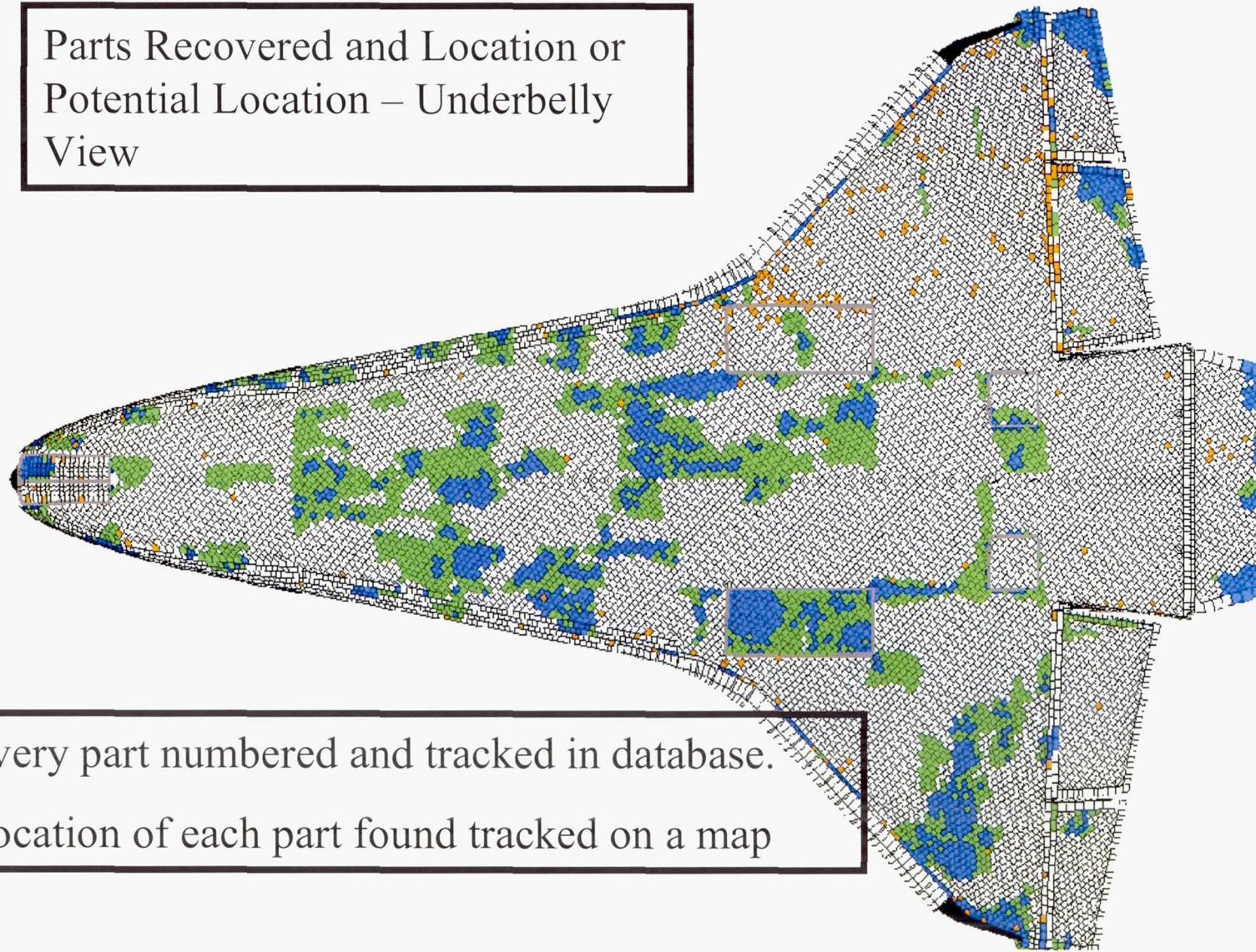


Left Wing Leading Edge Recovered Parts – Panels 1-22



Right Wing Leading Edge Recovered Parts – Panels 1-22

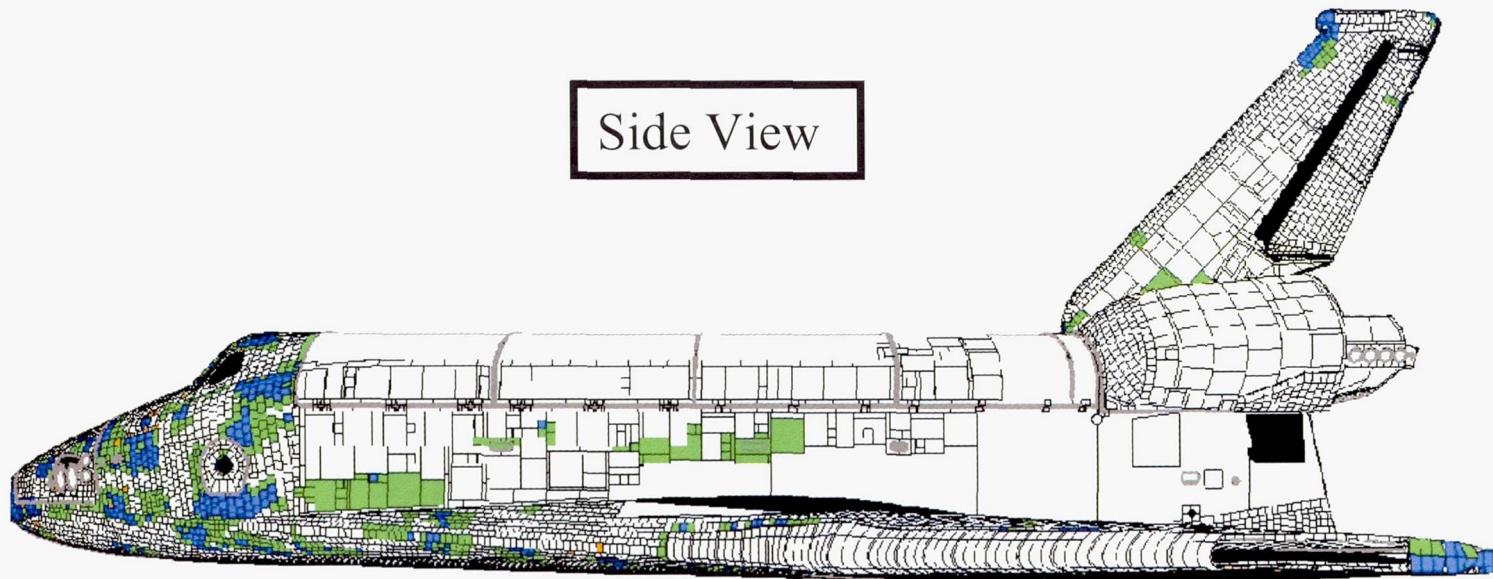
Parts Recovered and Location or
Potential Location – Underbelly
View



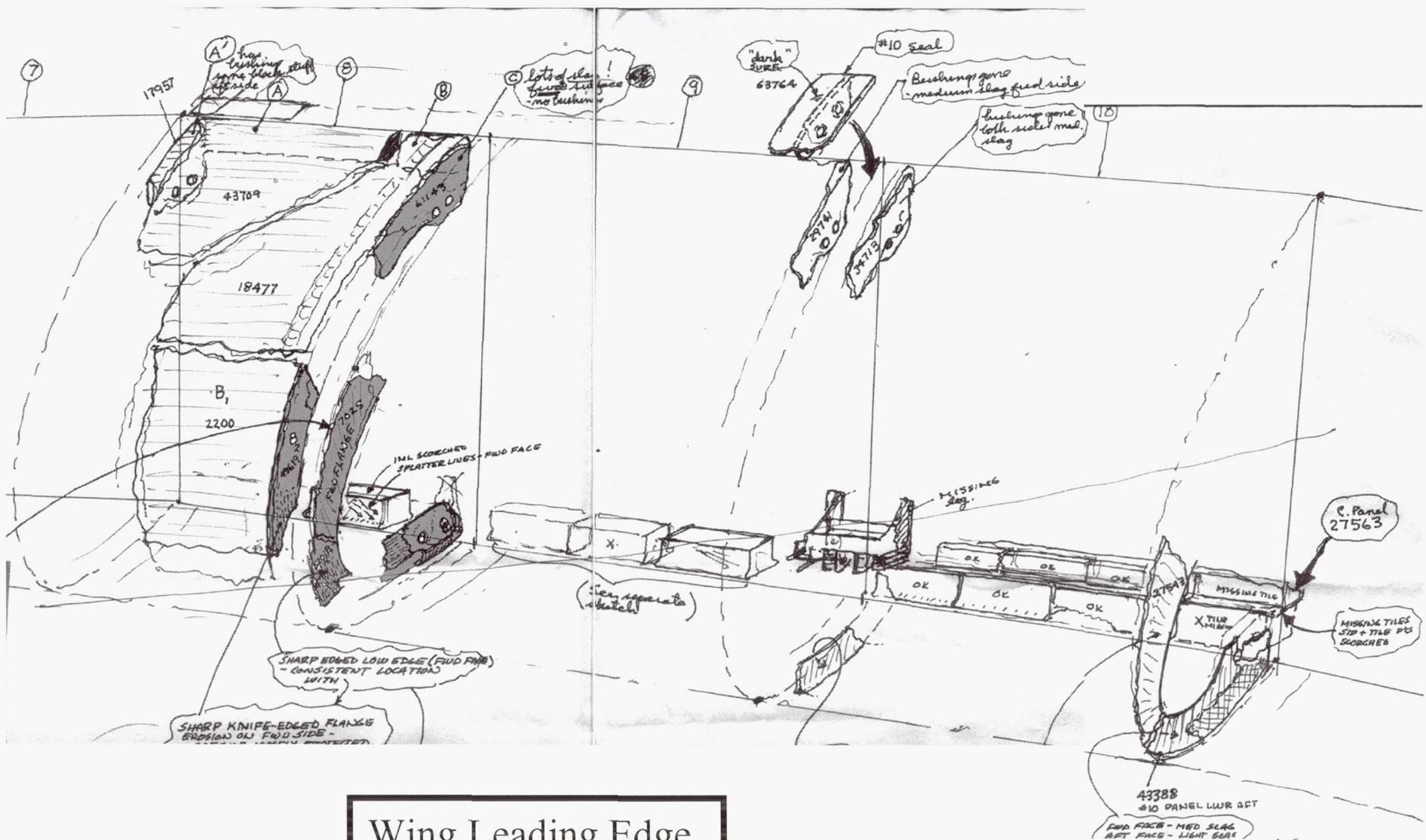
Every part numbered and tracked in database.

Location of each part found tracked on a map

Side View



Hardware Forensic Team Member Reconstruction Schematic & Notes



Wing Leading Edge



Left Wing Leading Edge
Final 3D Reconstruction



Left Wing Tile
Reconstruction

Leading Edge Tiles



STS107 Reconstruction Team

M&P Organizational Structure

- Hardware Forensics Team – “Gray Beard” members from Boeing, NASA Langley, NASA Johnson.
 - Evaluate Debris
 - Interact, disseminate and apply findings with other working groups (reconstruction, scenario, fault tree, etc.)
 - Direct specific Failure Analysis. Participate in determining Cause of Failure.
- Materials & Processes Problem Resolution Team.
 - Establish procedures – sample extraction, cleaning...
 - Interface with Hardware Forensics Team.
 - Generate Failure Analysis Plans.
 - Execute Failure Analysis Plans. Provide “Concrete Data”
 - Members included Boeing, USA, NASA KSC, NASA JSC,
NASA MSFC, NASA GRC

When and Where to Begin Failure Analysis?

- Complex and Challenging Analysis.
- New material added weekly.
- Parts originally located could move as more parts are received.
- Where to Begin? What Questions to ask?
- How many parts to analyze?
- Who to and how to prioritize Failure Analysis?
- How to distinguish between damage in flight vs free fall and impact.
- Initial Constraint – Perform all analysis locally at KSC. Parts could not be sent outside even to other NASA centers.
- CAIB owned the hardware. NASA only in support role.
- Every step/analysis/procedure required documentation through approval from CAIB and NAIT.

When and Where to Begin Failure Analysis?

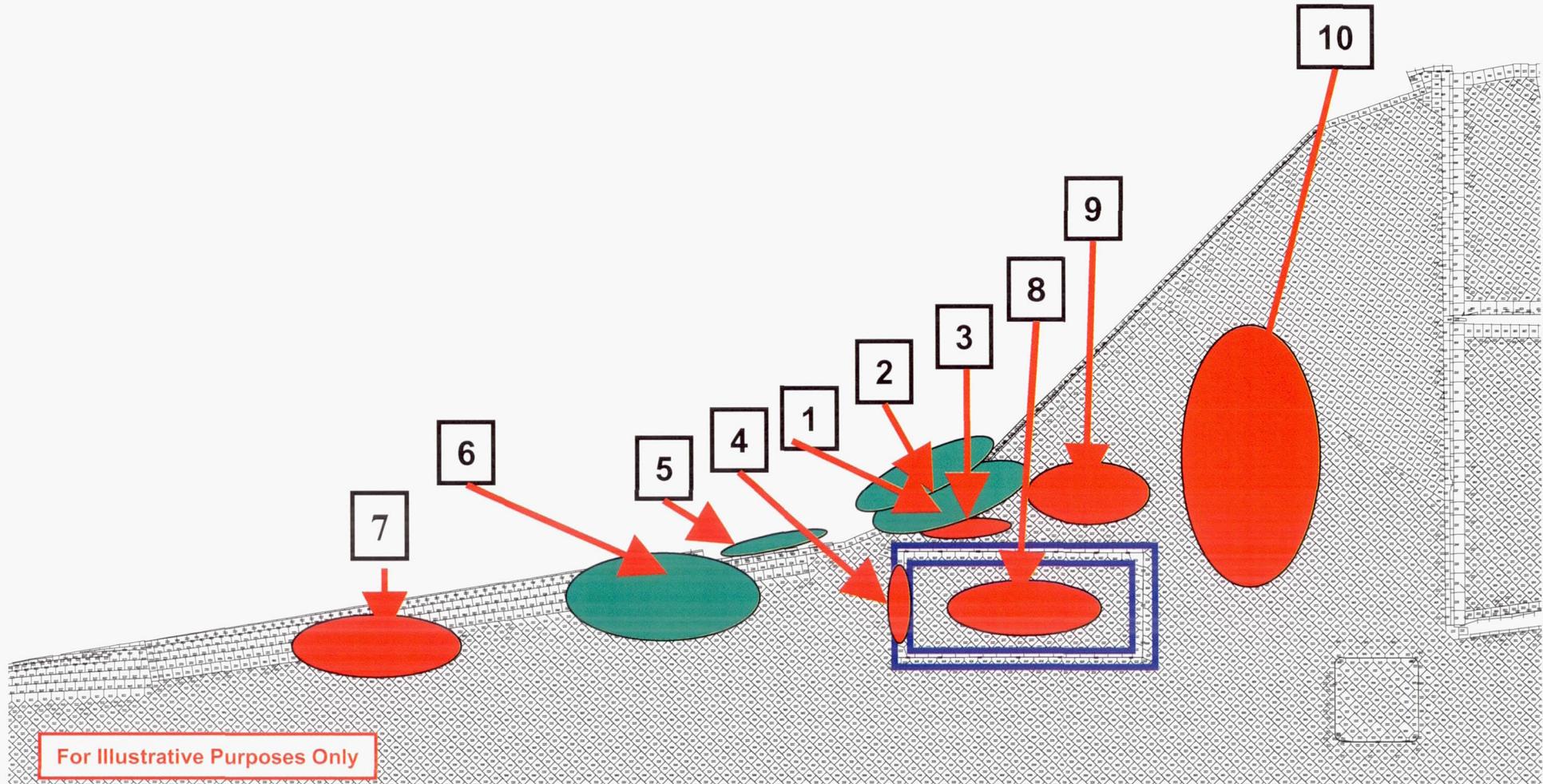
- Breach suspected in Left Wing.
- Begin with Factual Observations (Fact Sheets)
- Let Factual Observations guide the initial analysis.
- Initial Failure analysis included Left Wing:
 - Midbody Panel
 - Main Landing Gear Strut
 - Uplock Rollers
 - Tires
 - Leading Edge Carrier Panel Fastners
 - Tiles
 - **Leading edge RCC material deposit**
- M&P Failure Analysis Leads were assigned for each₂₁

Highest Level Questions

- Where (location in vehicle) did breach(es) occur?
- What specific component(s) failed and how?
- What was the sequence of events?

Initial Failure Scenarios and Breach Locations – April 14th, 2003

Scenarios Team

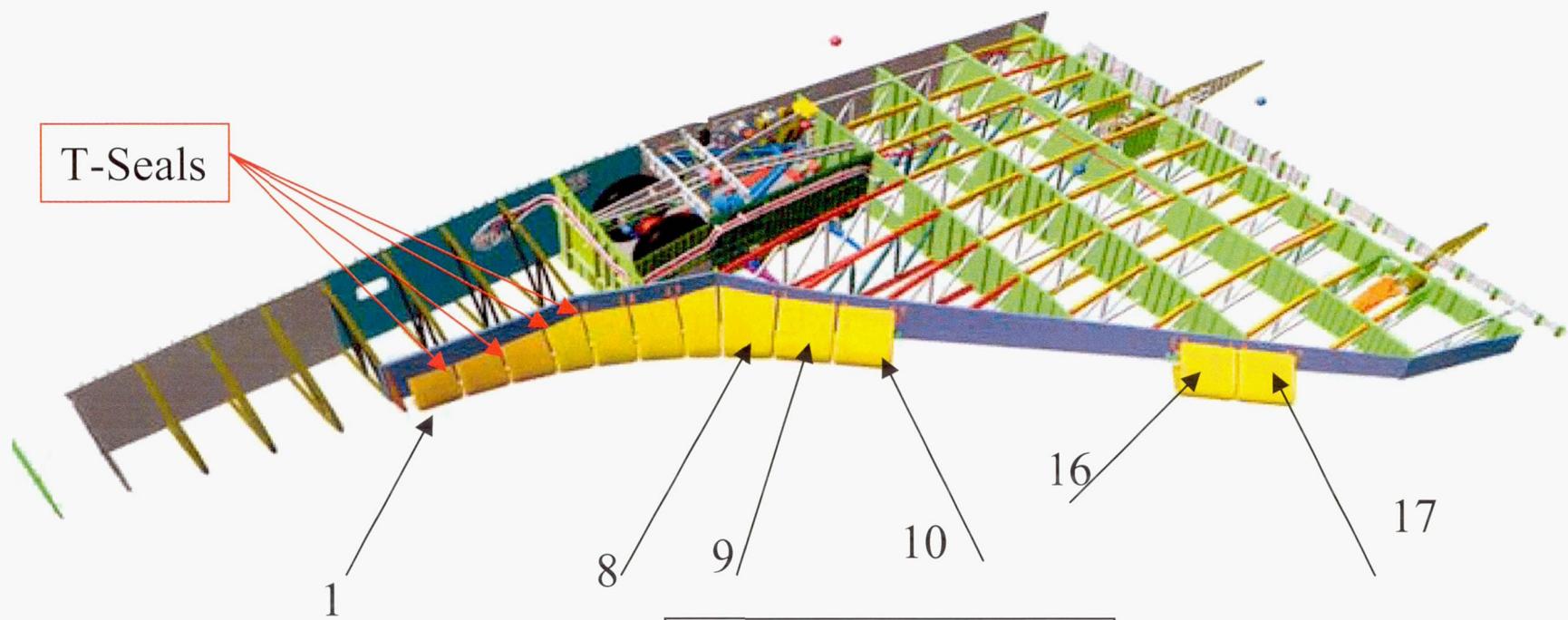
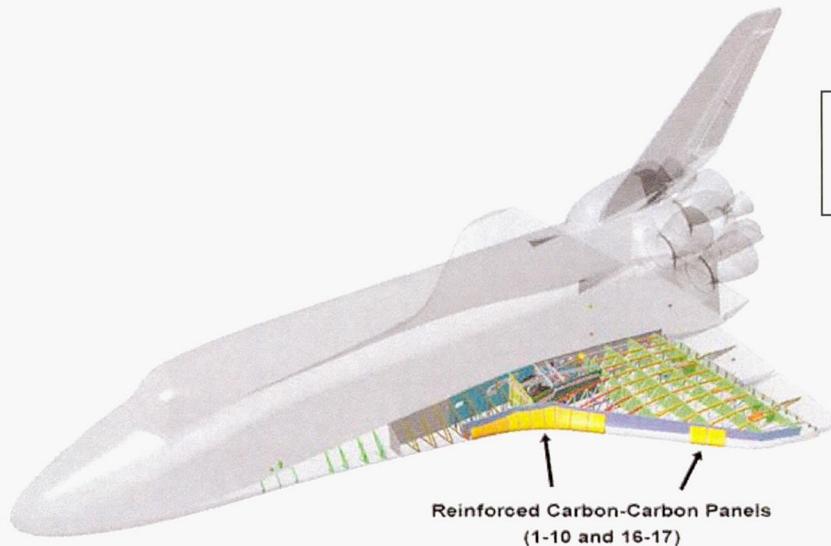


Key Finding

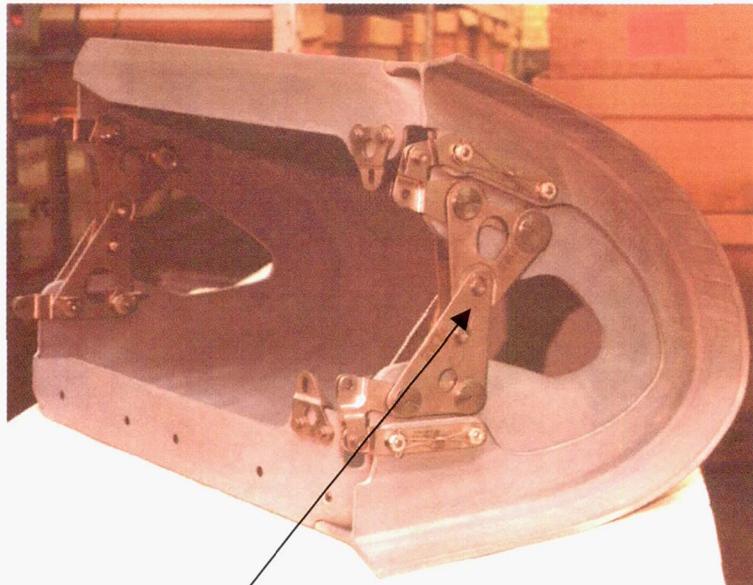
- MADS/OEX Data Recorder Found—“black box”.
- Key thermocouple inside and outside left wing leading edge panel 9.
- Temperature in this location starts increasing prior to early debri observations.

Spotlight/focus shifts to Left wing leading edge damage

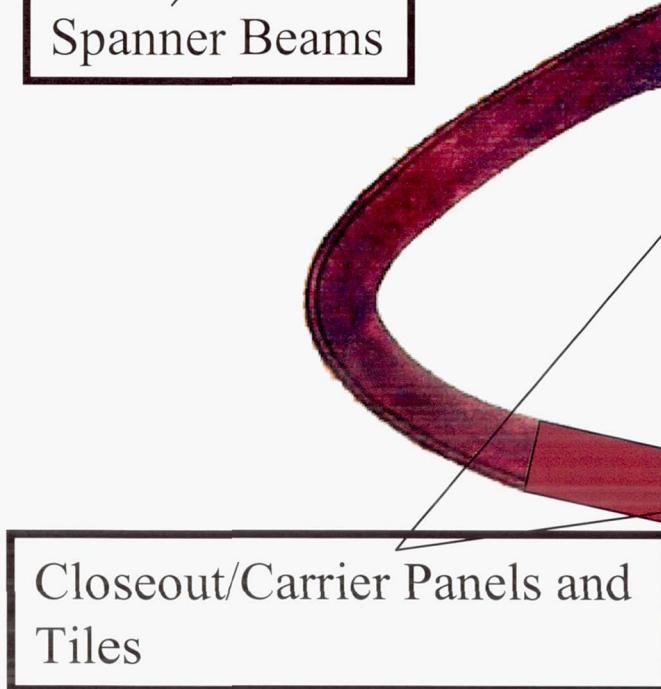
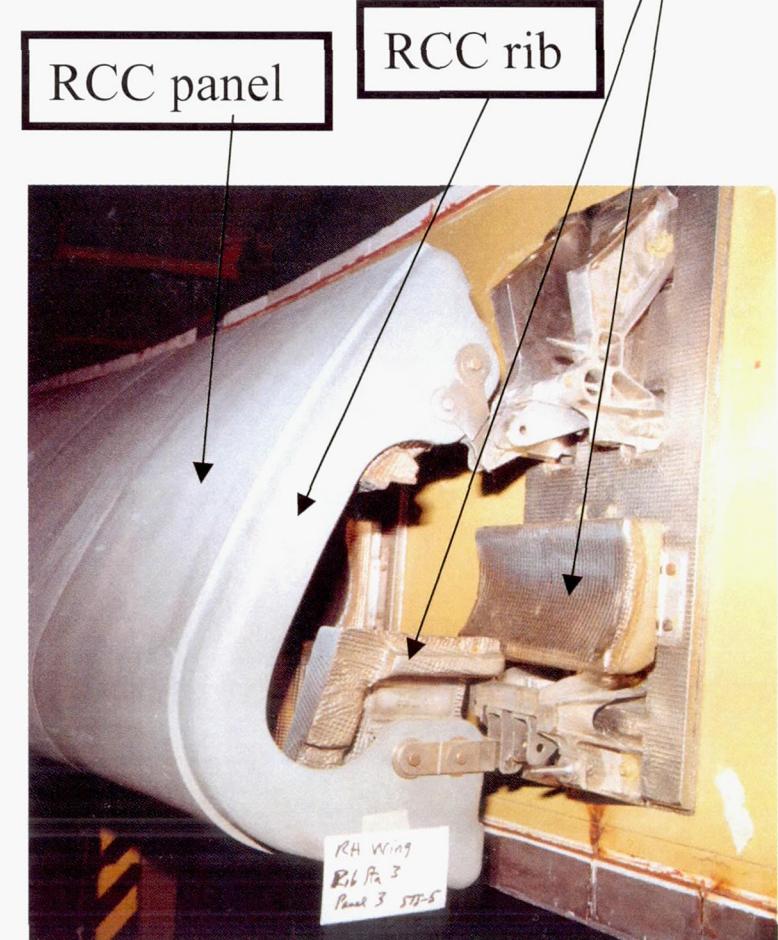
Left Wing Leading Edge



RCC Panel Numbers



Dynaflex insulation – In601 foil with cerachrome fibers inside

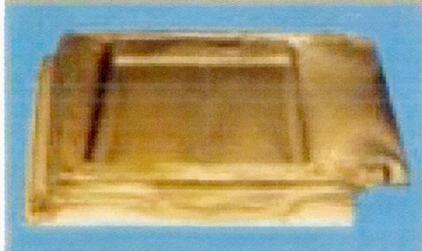


	RCC		Inconel-Dynaflex
	Aluminum		Inconel 718
	LI2200		A-286 steel
	LI900		

Space Shuttle Wing Leading Edge System



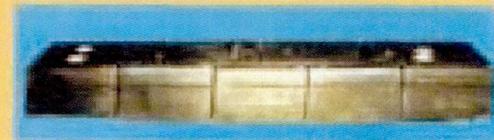
Ear Muff Insulation



Spar Insulation



RCC Wing Panel



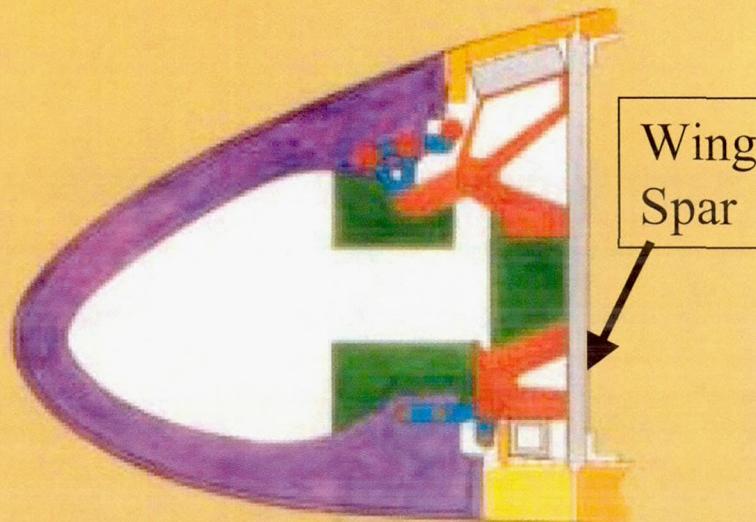
Upper Access Panel



Attachments
Inconel 718 A-286



Lower Access Panel

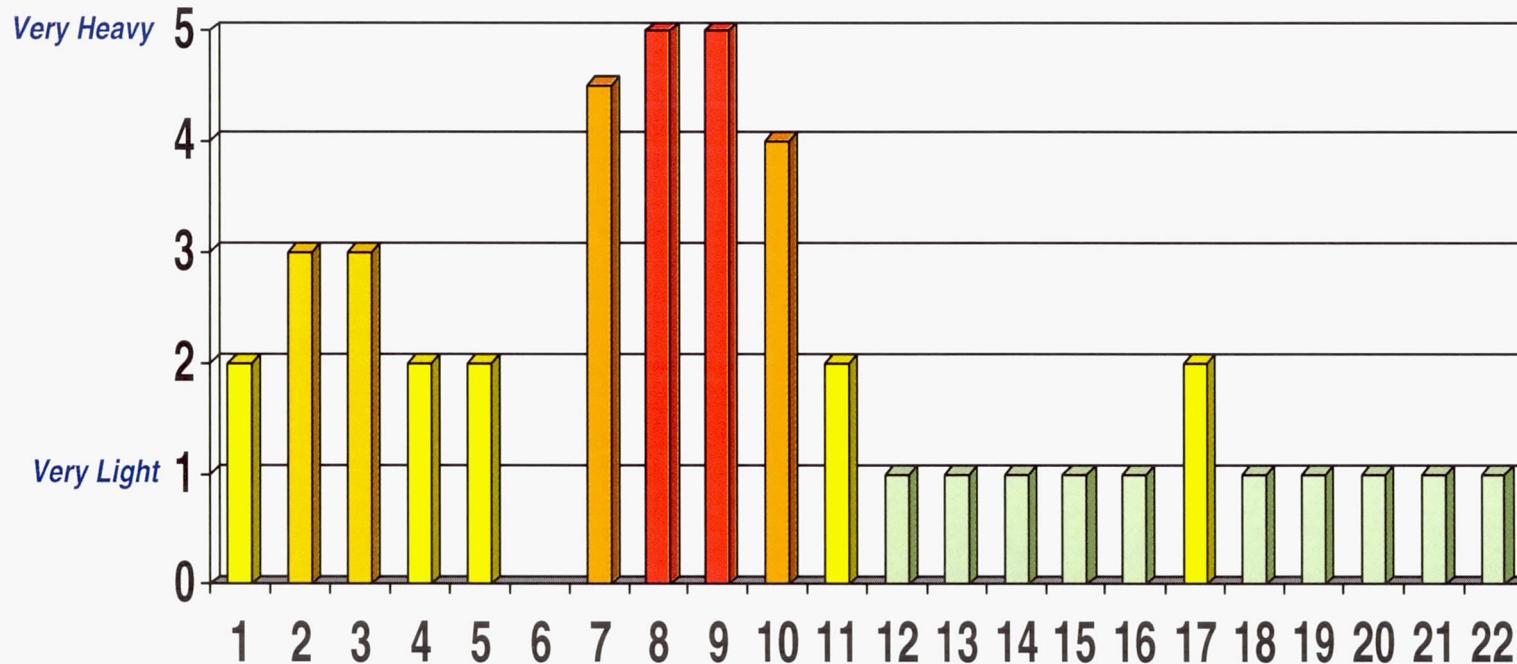


LI2200	Inconel 718	RCC	Inconel-Dynaflex
LI900	A-286 steel	Aluminum	

Left Wing Leading Edge Heat Damage Observations

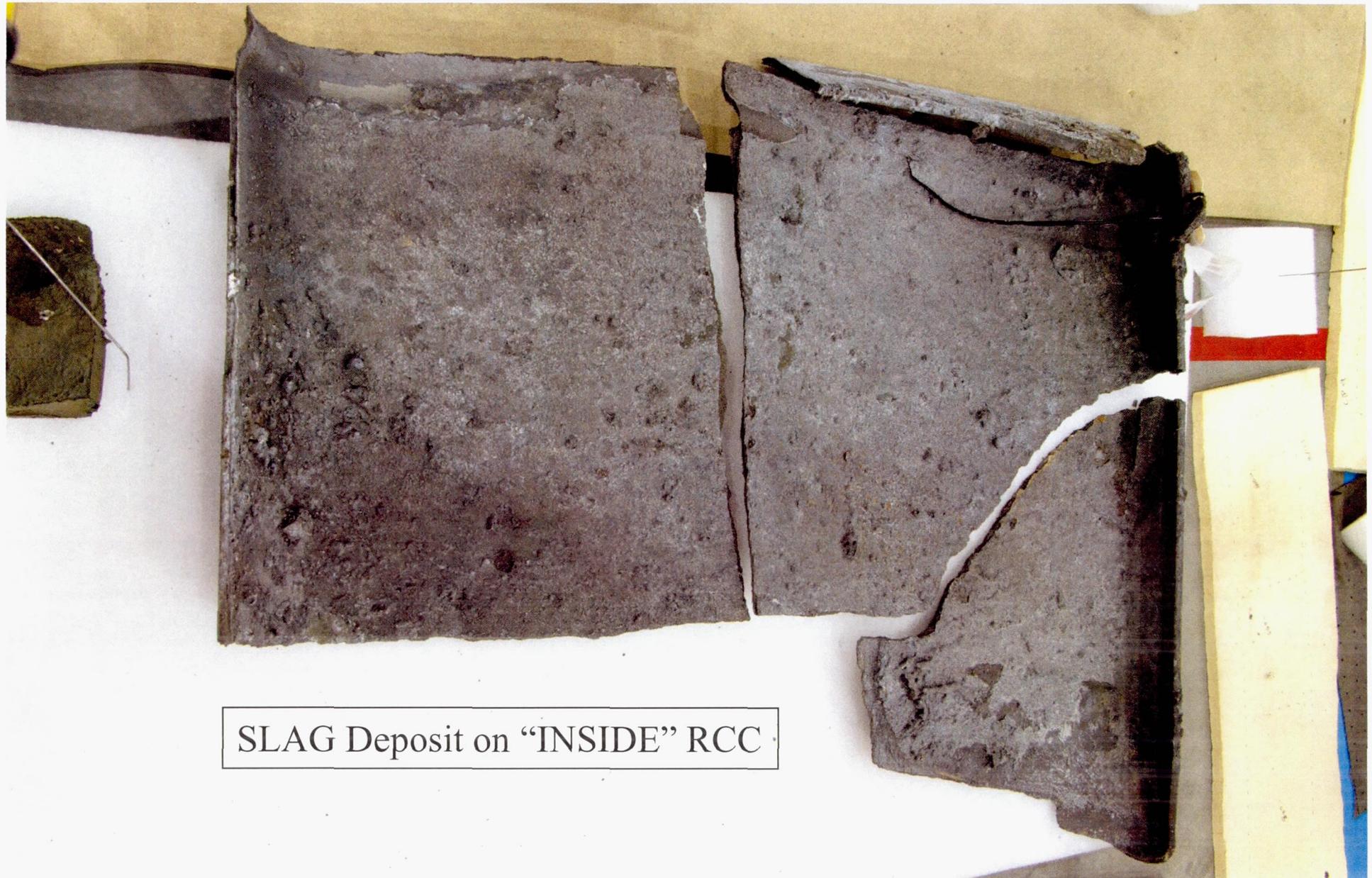
- Heavy “Slag” deposits on select RCC panels.
- Eroded and knife-edged RCC rib sections.
- Excessive overheating and slumping of carrier panel tiles.
- Missing or molten attachment bolts but intact bushings.
- Deposit mainly on “inside” RCC panel.
- Deposit on some fractured RCC surface.

Qualitative Deposition Assessment: “Very Light” to “Very Heavy”



Distribution of “slag” deposition volume
was centered around panels 8 & 9 on Left Wing Leading
Edge RCC.

Example Debris, LH RCC 8



High Level Questions

Sample the slag deposits on RCC & Tiles to:

- Identify the location of breach in the wing leading edge.
- Identify the sequence of deposition/events
- Understand plasma flow direction and related thermal damage.

Analysis Plan Challenges

- Understand Pros and Cons of Analysis Techniques (destructive and non-destructive)
 - Objective is to downselect analysis techniques fast.
- What are the leading edge materials?
- Understand Chemistry of reactions with atmospheric elements.
- Understand effects of melting and mixing of different materials.
- All analysis to be complete by end of May, 2003.
Wrap-up in June.

Analysis Techniques

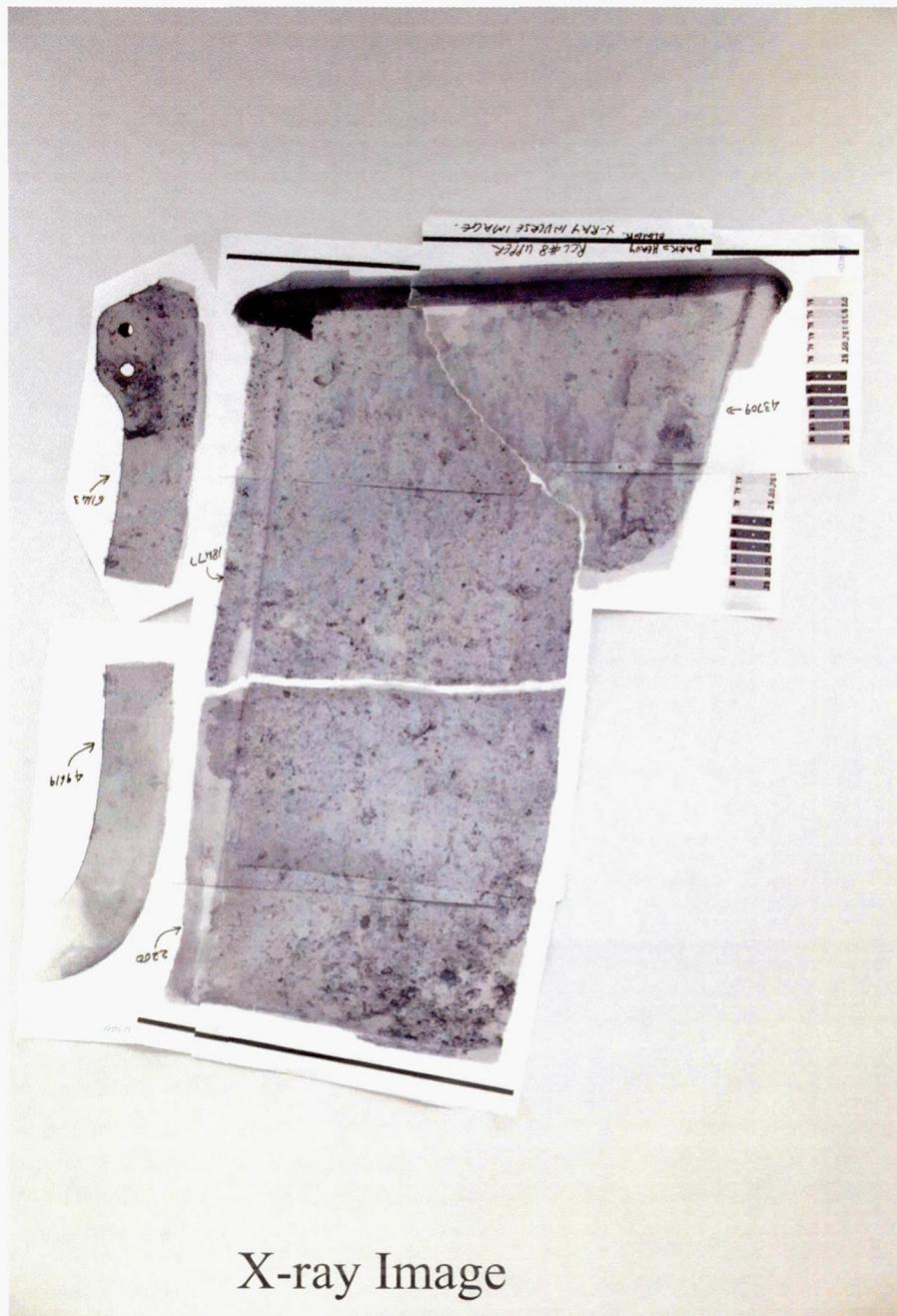
Analysis Technique	Purpose	Why/Advantages
Photography	Photo documentation	Documentation to maintain traceability
Scanning Electron Microscopy – SEM/EDS	Semi-quantitative elemental composition	Elements present, identify difference between top and bottom of sample
X-ray Diffraction - XRD	Identify compounds	Identify compounds of crystalline structure
Electron Microprobe	Identify elements	Determine exact composition
Fourier Transform Infra-Red - FTIR	Qualitative organic composition	If organic, aid in identification
ESCA/XPS	Identify inorganic & organic compounds	Aid in tracking of oxidation states, such as oxide; compound identification
Metallography + SEM	Layering of material	Composition through deposit layers
Inductively coupled plasma - ICAP	Quantitative elemental composition	Elements present, Quantify bulk composition of sample
NDE Inspections- Radiography , CT, Ultrasonics	Non-destructive Inspection and identification	See through the material, identify differences in materials, identify defects

Repeatability and Reproducibility of results emphasized

Approach and Downselection of Analysis Techniques

- Radiograph RCC panels & Tiles
- Strategically locate samples - minimize the sample count. **Two samples of each feature.**
- Use diagnostic techniques (X-section, SEM, Microprobe, XRD) to identify:
 - Content of slag
 - Layering of slag
- Use “Interpretation Criteria” to correlate deposit analysis <==> WLE source material

Apply results to ALL radiographs and visual features to answer the high level questions.



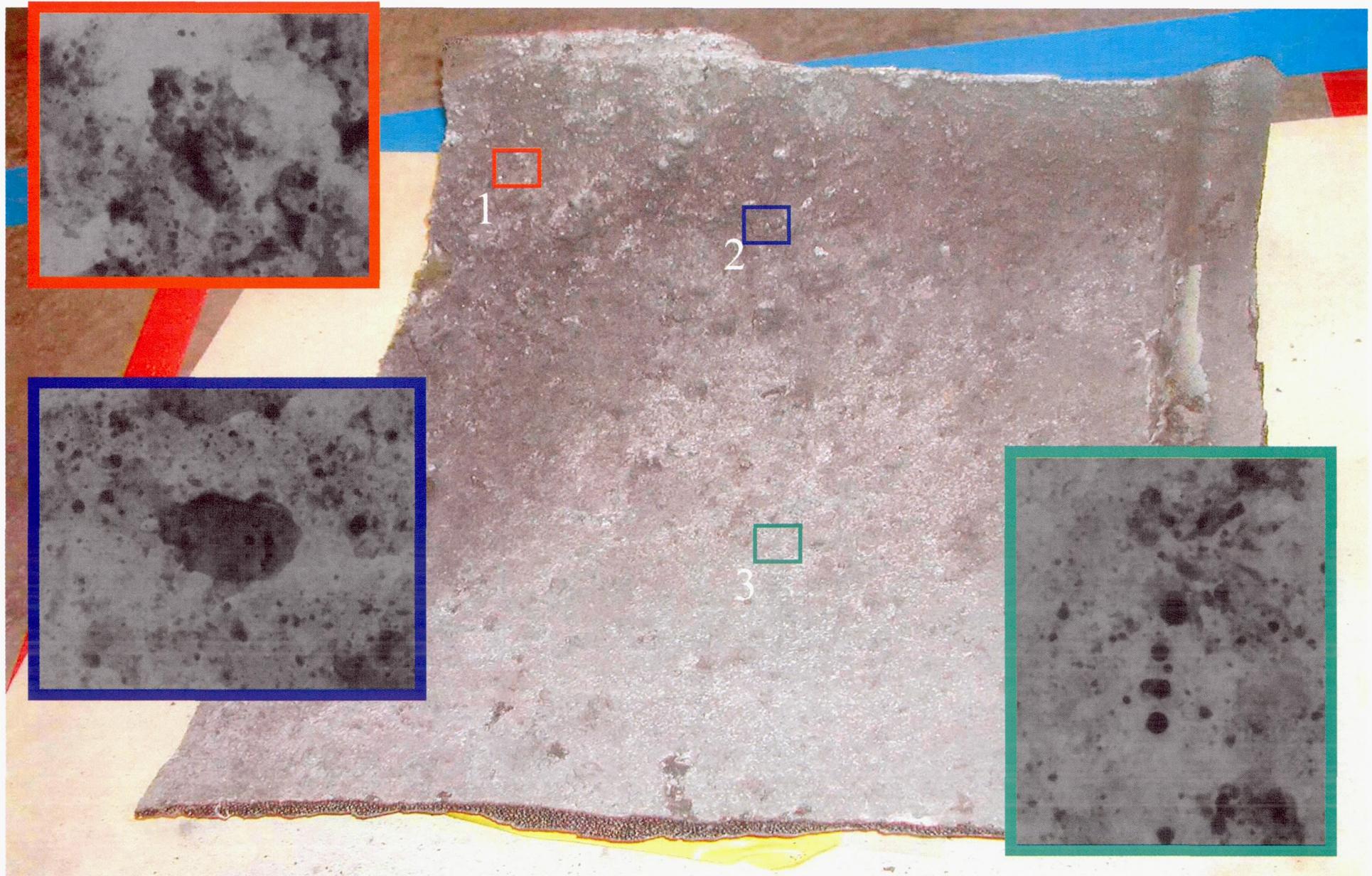
X-ray Image



Hardware

Left Wing RCC panel 8. Inside View.

2200, LH RCC #8 Upper Apex, Part I,
Matches 18477

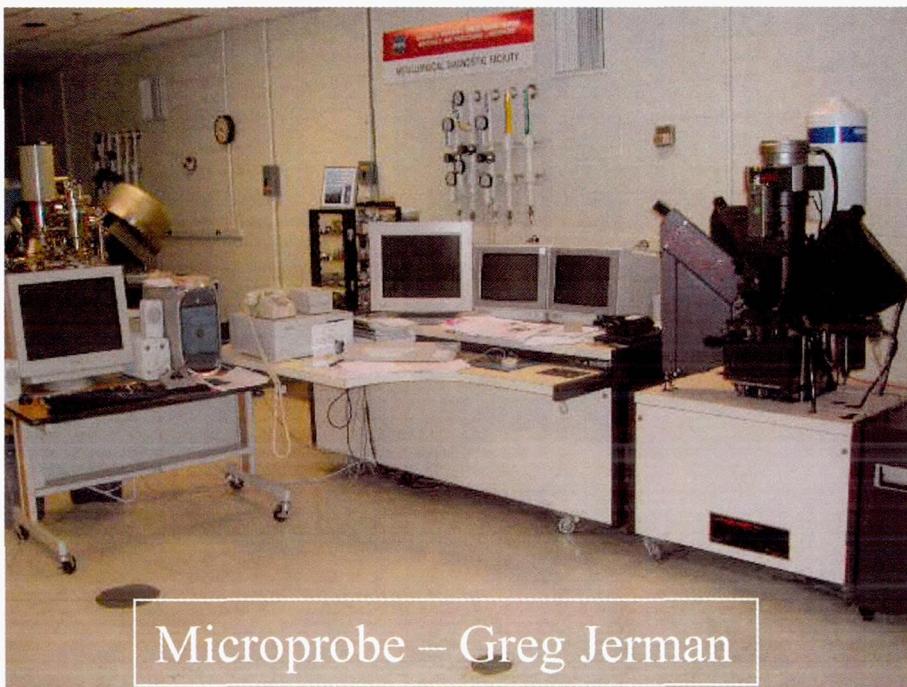


Interpretation Criteria - Examples

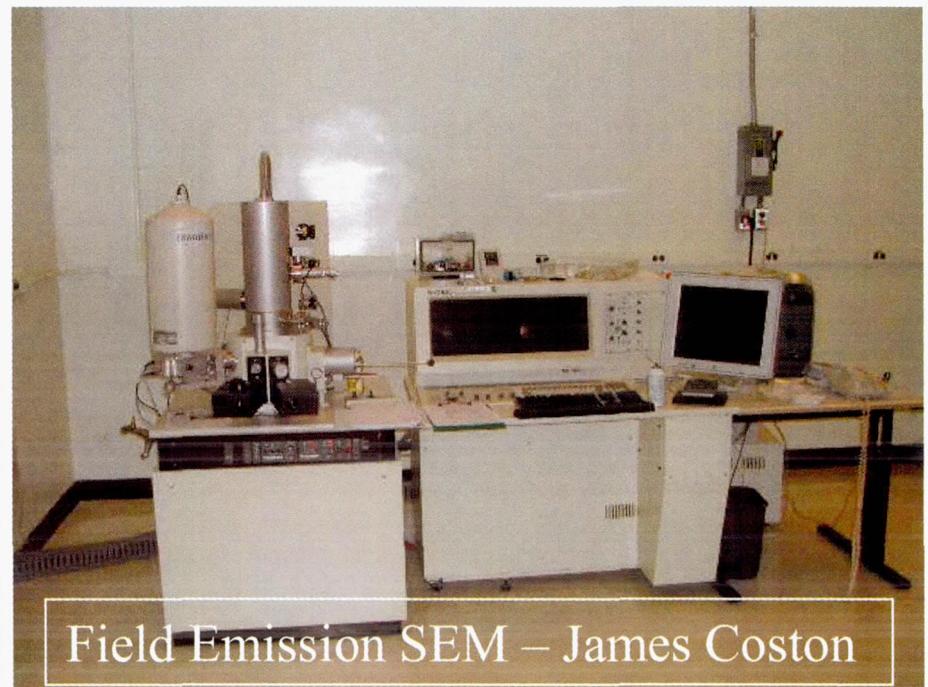
- **How to identify specific alloys in the deposit?**
 - A286 or IN601, IN718, IN625 can be distinguished based on (Ni/Fe) ratio and evidence and amounts of Mo, Nb, Co and Ti.
 - 2024 can be identified by presence of metallic Al + Cu, Al_2O_3 + Cu.
- **How to identify Cerachrome in deposit?**
 - Cerachrome is approximately 43% Al_2O_3 53% SiO_2 3% Cr_2O_3 .
 - It can be identified from a combination of back-scattered imaging, color, x-ray diffraction and presence and quantification of Al, Si, O, & Cr.
- **How to identify SiO_2 from Tile?**
 - SiO_2 from tile will not have with other elements as in cerachrome. It could still pick up a coating of alumina then morphological features will be used to distinguish.

MSFC Contribution

- Help Organize, Plan, and Co-ordinate all sampling activity.
- Metallography, Microprobe, & SEM.
- Generated 1000 pages of data & reports in 6 weeks.



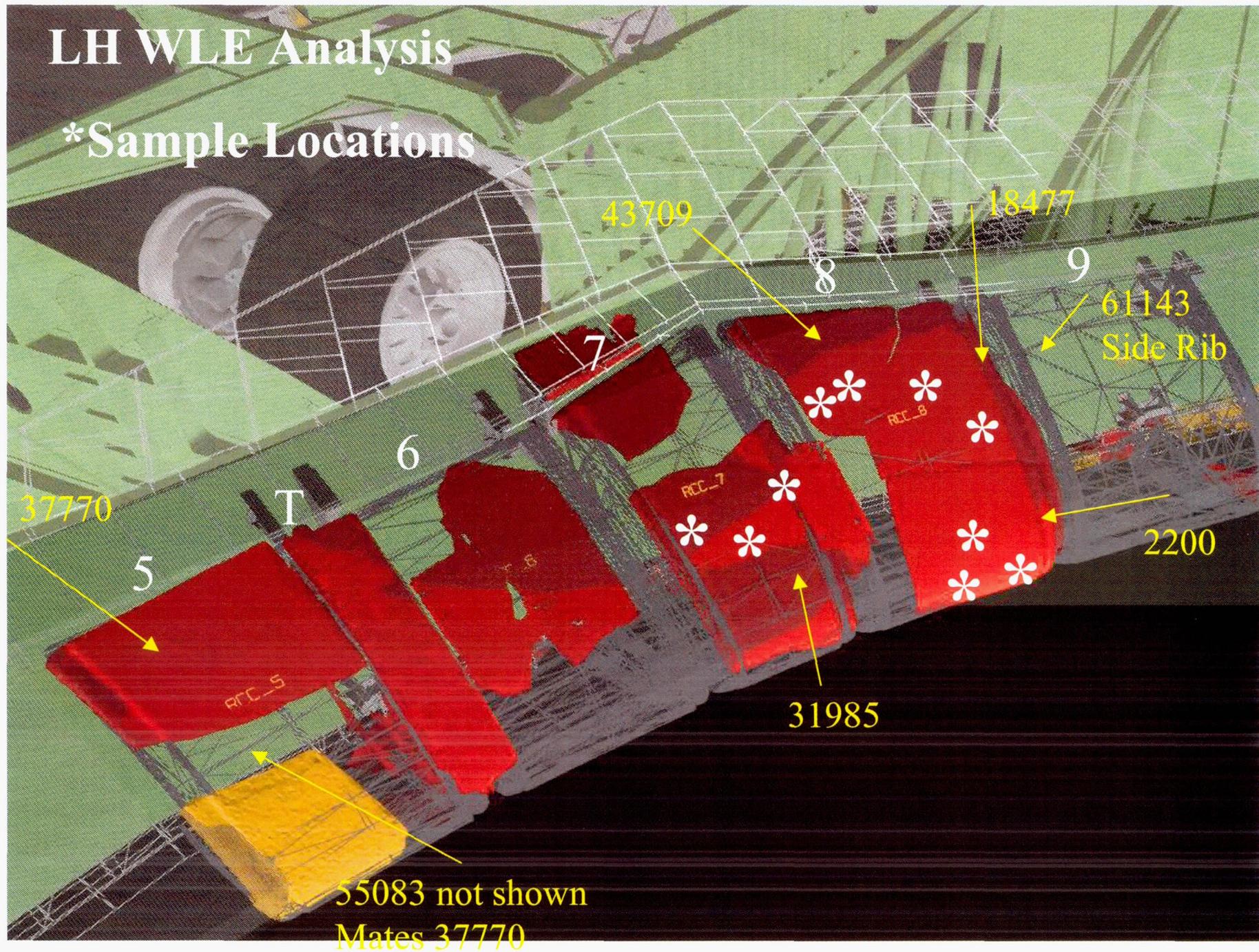
Microprobe – Greg Jerman



Field Emission SEM – James Coston

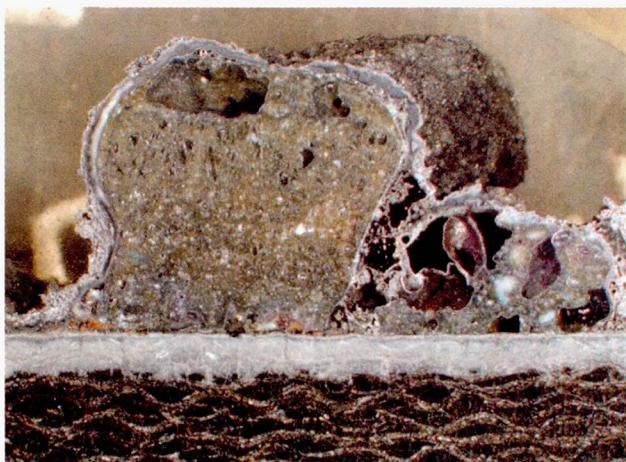
LH WLE Analysis

*Sample Locations

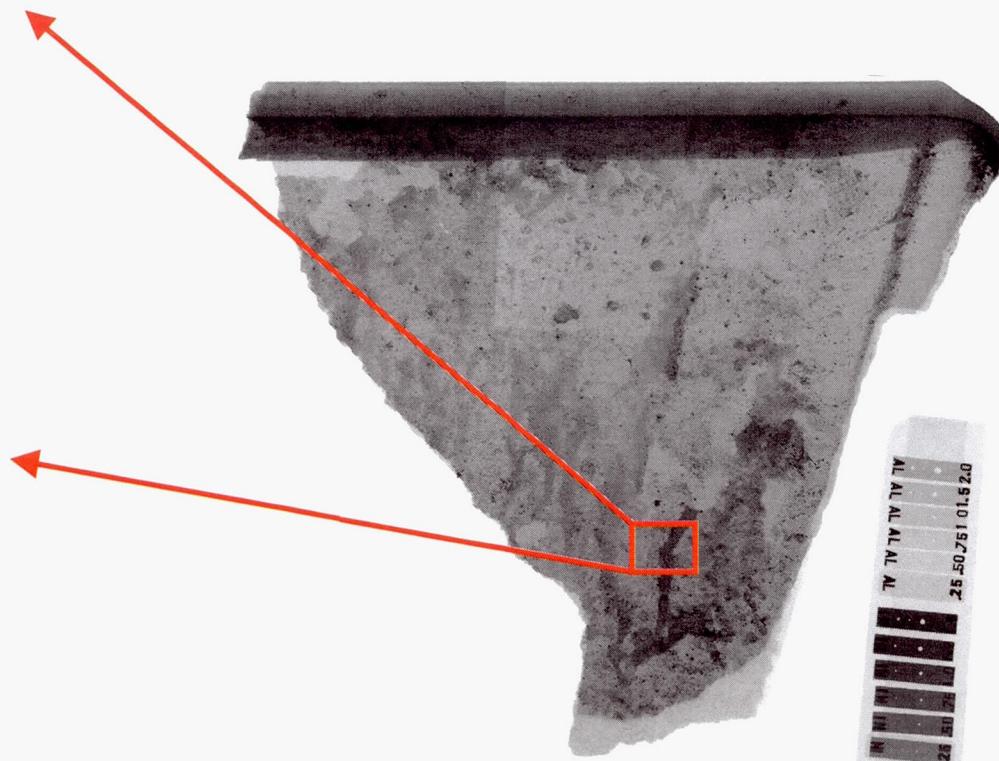


LH RCC #8 - Slag Feature 1

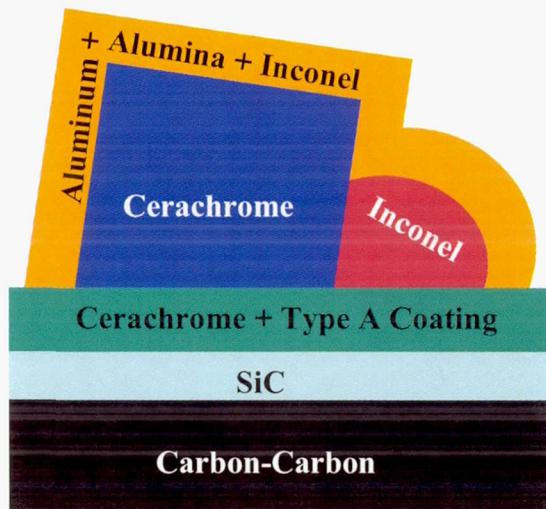
Thick Tear Shaped



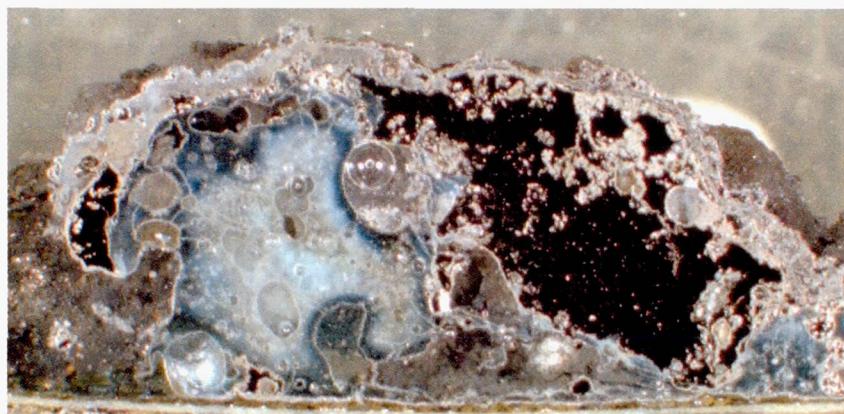
Slag Item 43709, Sample 2A1



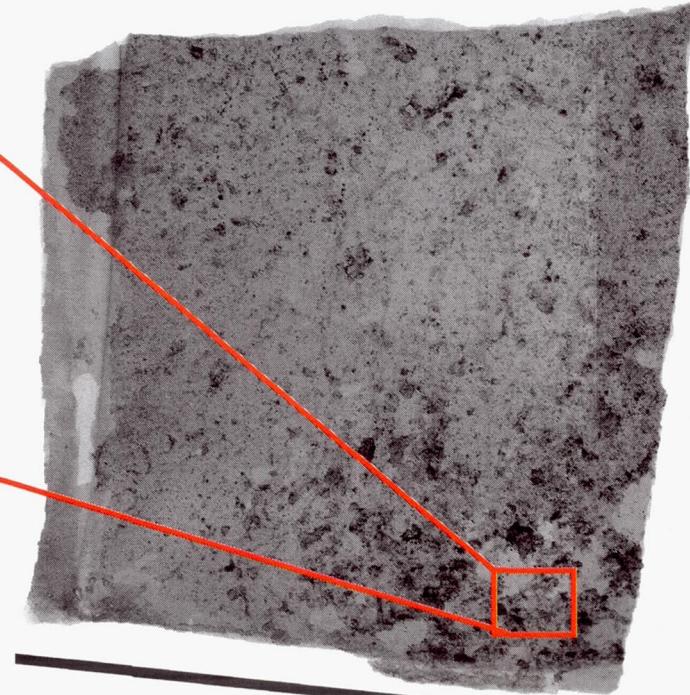
Radiograph of Item 43709



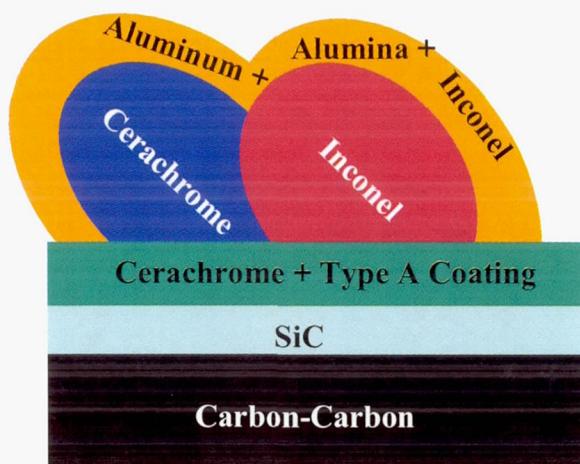
LH RCC #8 - Slag Feature 2 Thick Globules



Slag Item 2200, Sample 6A1



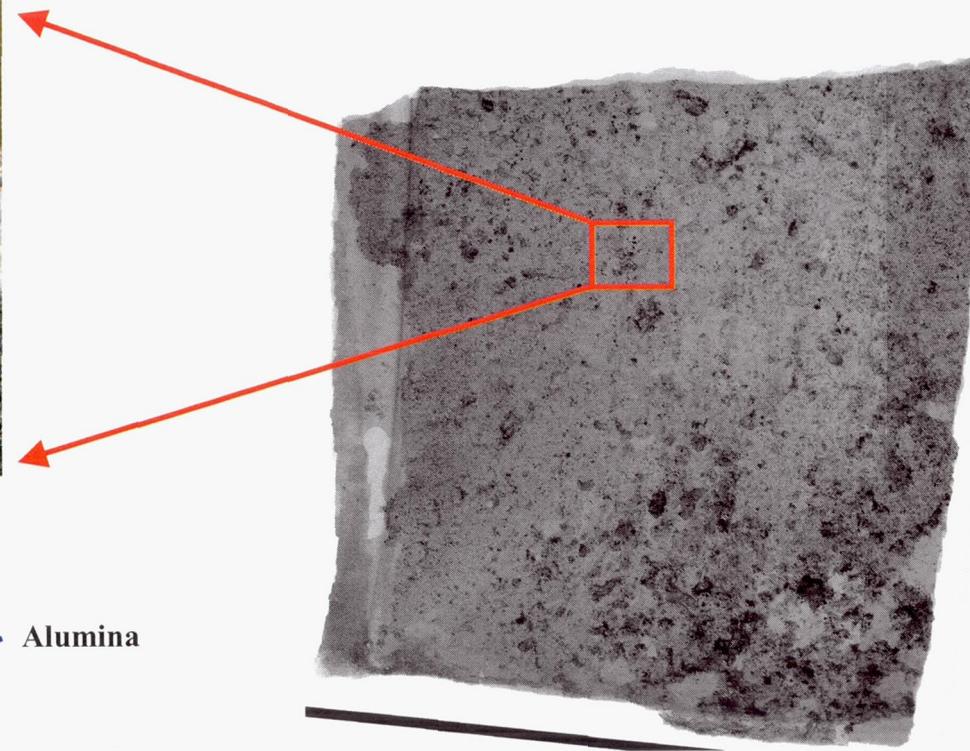
Radiograph of Item 2200



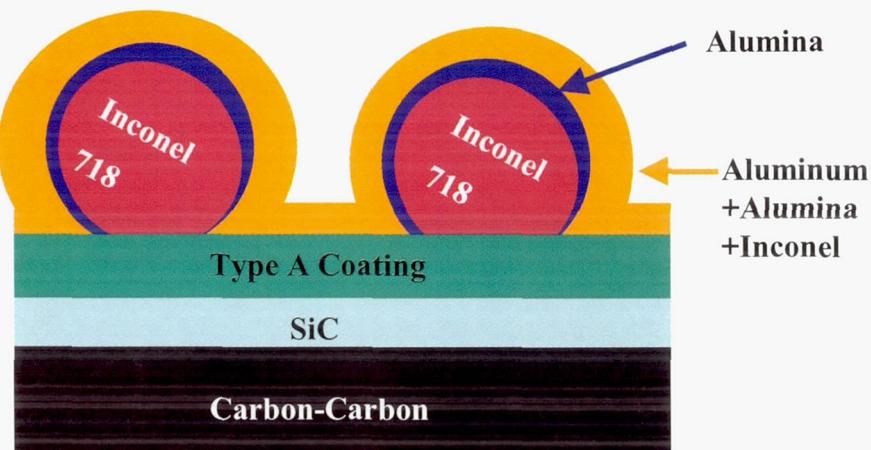
LH RCC #8 - Slag Feature 3 Spheroids



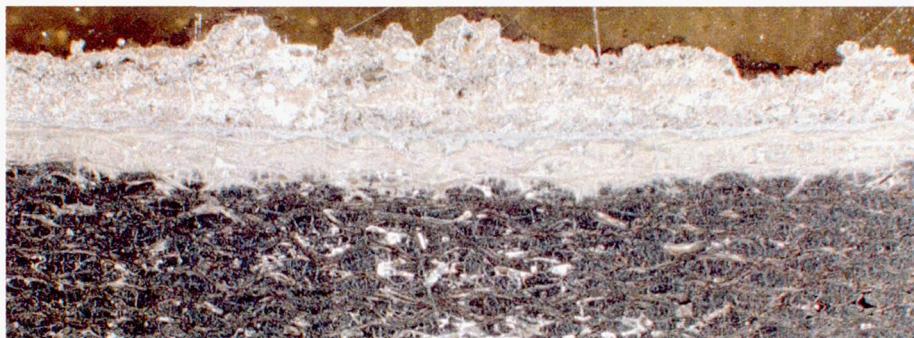
Slag Item 2200, Sample 6C1



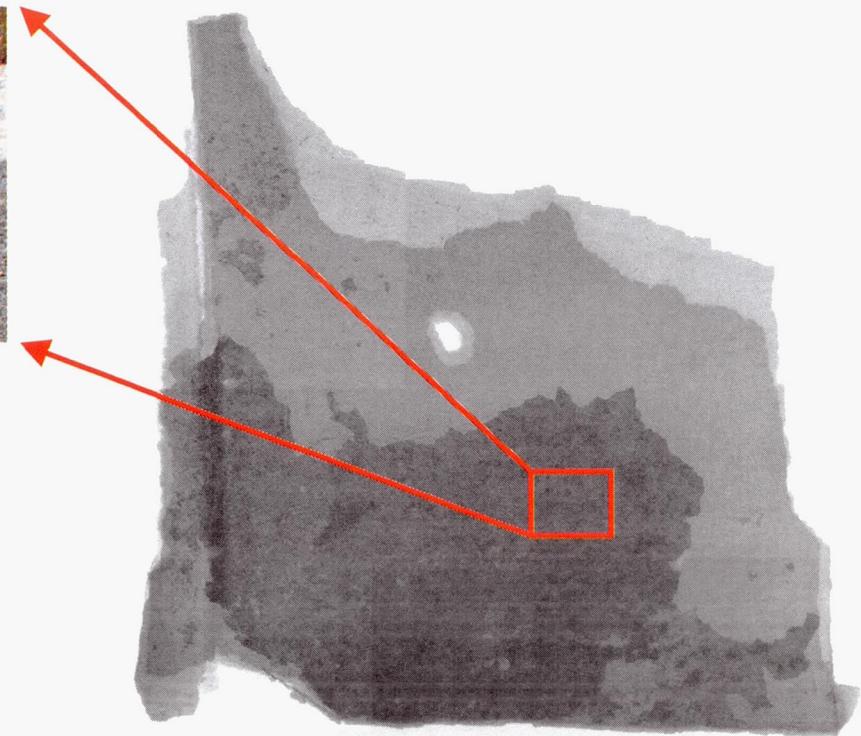
Radiograph of Slag Item 2200



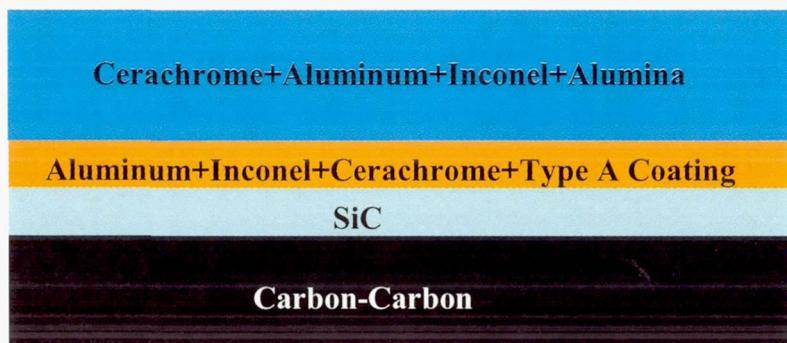
RH RCC #8 - Slag Feature 4 Uniform Deposit



Slag Item 16523, Sample 4A1



Radiograph of Item 16523



RCC Slag Significant Findings

LH RCC #8

- Large amounts of melted ceramic cerachrome insulator
 - High temperature $>3200^{\circ}\text{F}$
- No indication of stainless steel spar fittings (A286) in slag
 - Breach location away from spar fittings
- Cerachrome + Inconel in first deposited layers
 - Melting of spanner/foil/fittings + Insulator
- Aluminum deposition secondary event

Slag layering suggests plasma impingement location

Slag distribution & shape suggests plasma flow direction and deposition duration

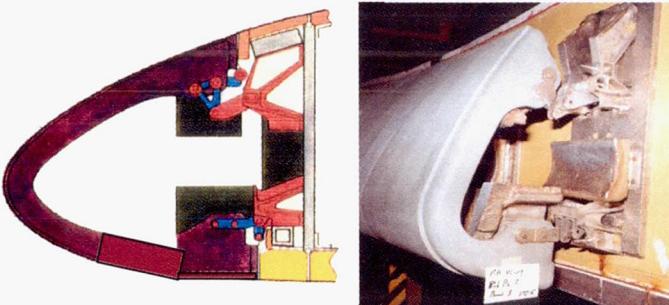
RCC Slag Significant Findings

-All RCC other than LH RCC #8

- Including RH RCC panels

- All analyzed slag layers contain aluminum
 - CONCURRENT Spar/Inconel/Insulator melting
- Slag is generally uniform and relatively thin
 - No region where melting was concentrated i.e. plasma heating for short periods

Reconstructed View LH CPanel 9 Tiles, lower



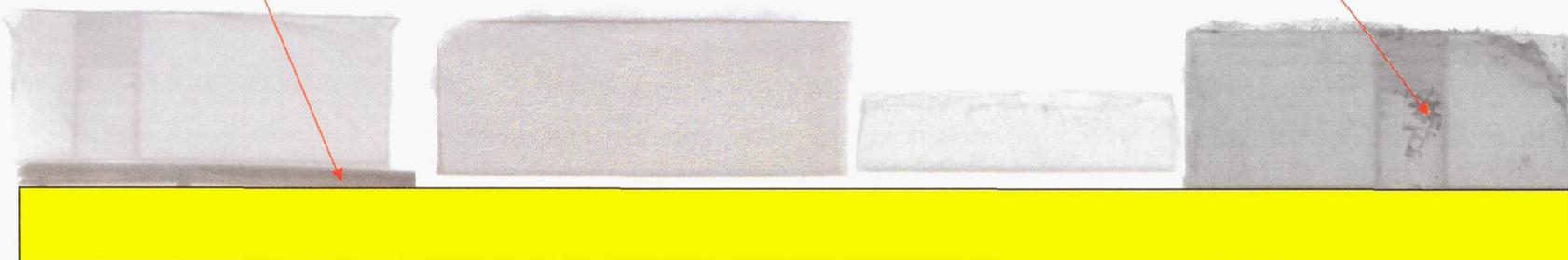
C
P
8

Spar
RCC

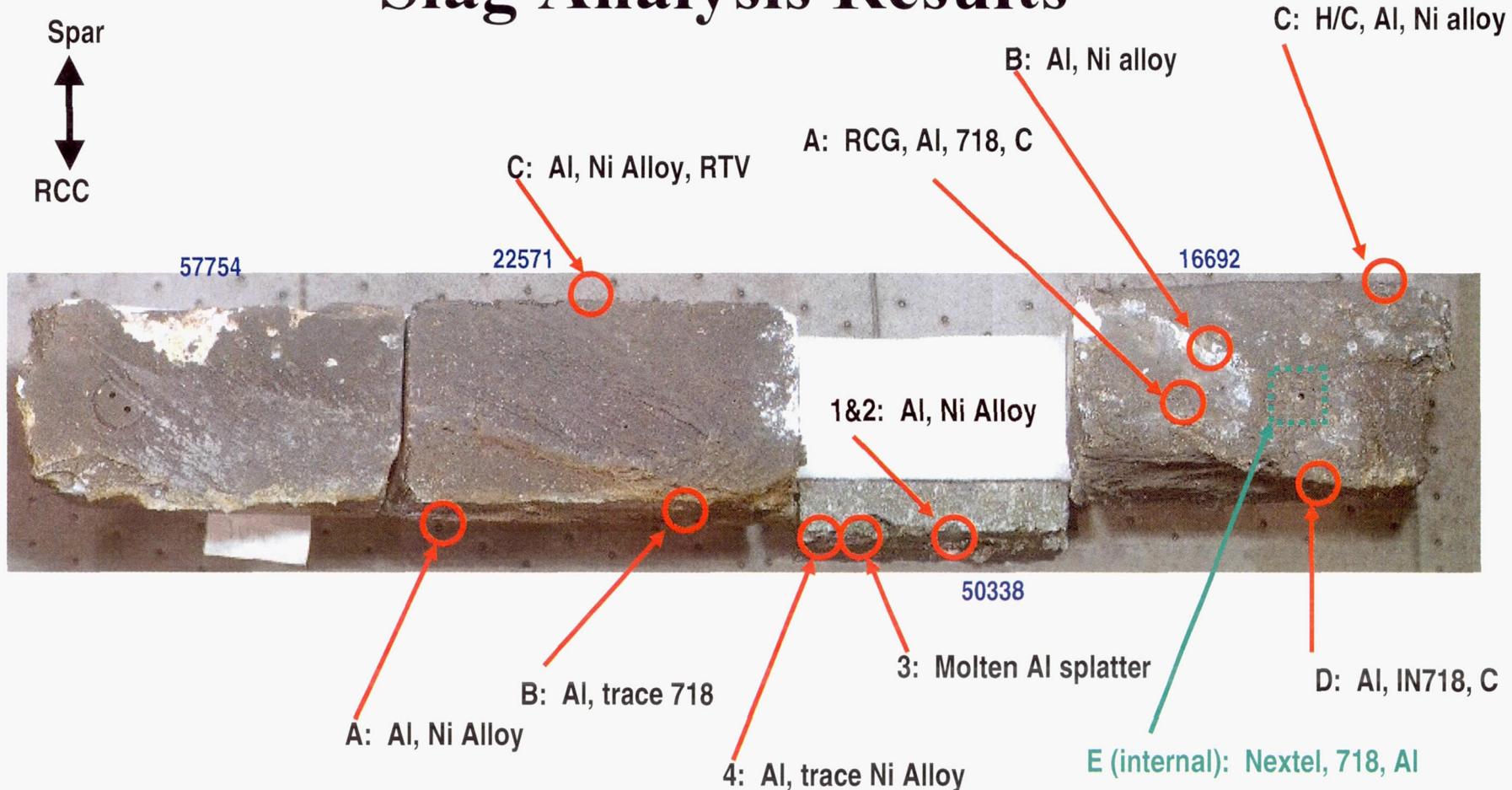
Carrier Panel

High-Z material

Realtime X-ray, Sidewall View



Reconstructed View LH Carrier Panel 9 Tiles, Lower Slag Analysis Results



These findings suggest flow of material from inside the RCC out through the upper and lower CP locations.

Proposed Breach Location & Plasma Flow Based On Slag Results

